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(54) Title: METHODS AND APPARATUS FOR MEASURING NAVIGATIONAL PARAMETERS OF A LOCOMOTIVE
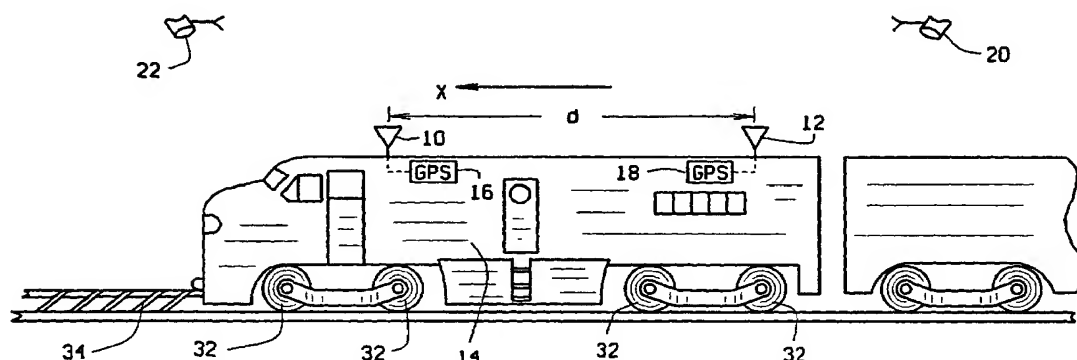
(57) Abstract: The present invention, in one aspect, is a method for determining motion and/or location parameters of a locomotive. One method embodiment includes steps of phase locking a pair of receivers having antennas at different locations on a locomotive to reference signals received from a set of satellites, determining a set of phase differences between the reference signals received at the antennas, and determining at least one of an accurate heading, heading rate, attitude, and attitude rate of the locomotive using the set of phase differences between the reference signals.

METHODS AND APPARATUS FOR MEASURING
NAVIGATIONAL PARAMETERS OF A
LOCOMOTIVE

CROSS REFERENCE TO RELATED APPLICATIONS

This application claims the benefit of U.S. Provisional Application No. 60/153,304, filed September 10, 1999, which is hereby incorporated by reference in its entirety.

BACKGROUND OF THE INVENTION

5   This invention relates generally to methods and apparatus for measuring navigation parameters of a locomotive, and more specifically to methods of determining movement and direction of a track-bound transportation apparatus using GPS satellites.

Modern algorithms for train navigation incorporate very sensitive turn rate gyroscopes (gyros) that permit detection of low speed .through high number 10   turnouts such as a #20 equilateral turnout. These gyroscopes are quite expensive, and suffer from coning problems due to superelevation. In addition, measurement drift accumulates over time. This drift must be corrected periodically by reference to data in a track data base. It would therefore be desirable to replace gyroscopes (gyros) in such applications altogether or to provide an alternate system for determining heading 15   accurately for low speed and high speed turnouts. Where trains move over a curving track, the rails wear down due to friction between the wheels of the train and the rails. As used herein, a curve is represented by any change in path direction. Therefore, curving means that a path direction is changing. One solution to this problem is to provide lubricant to the rails or to the wheels when a train is moving. However, this 20   solution is wasteful of lubricant. It would therefore be desirable to provide a method and apparatus to more efficiently reduce rail wear on curving tracks by determining when a train is on a curve and by applying lubricant.

BRIEF SUMMARY OF THE INVENTION

There is therefore provided, in one embodiment, a method for determining motion and/or location parameters of a locomotive. This method embodiment includes steps of phase locking a pair of receivers having antennas at different locations on a locomotive to reference signals received from a set of at least three satellites, determining a set of phase differences between the reference signals received at the antennas, and determining at least one of an accurate heading, and/or heading rate of the locomotive using the set of phase differences between the reference signals.

The above embodiment can be implemented on a train using inexpensive satellite receivers and an inexpensive processor, and can be used in conjunction with a gyroscope having reduced specifications to provide accurate heading information in both low and high speed turnouts. In addition, the heading information provided by this embodiment can advantageously be used to reduce usage of lubricants applied to reduce track wear.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is a drawing of a locomotive showing a relative location of receiving antennas of one embodiment of the present invention installed thereon;

Figure 2 is a diagram of an embodiment of a heading and attitude system of the present invention;

Figure 3 is a top view of a locomotive on a curving track;

Figure 4 is a drawing of a locomotive engine showing an embodiment of a lubricant dispenser applying a lubricant to track rails;

Figure 5 is a block diagram of an embodiment of a rail lubricant control system of the present invention employing a gyroscope and a tachometer;

Figure 6 is a block diagram of an embodiment of a rail lubricant control system of the present invention employing two GPS satellite receivers and a tachometer; and

Figure 7 is a block diagram of an embodiment of a rail lubricant
5   control system of the present invention employing a lateral accelerometer and a tachometer.

DETAILED DESCRIPTION OF THE INVENTION

In one embodiment and referring to Figure 1, inexpensive carrier phase satellite, for example Global Positioning Satellite (GPS), receivers are used to determine train heading very accurately for low and high speed turnouts, which may
10   be used in locomotive nav-systems.

Two antennas 10, 12 are mounted along a longitudinal or lateral axis x of a locomotive 14 or train car at a known distance d apart. Antenna 10 and antenna 12 feed separate carrier phase GPS receiver 16 and GPS receiver 18, respectively. Receivers 16 and 18 lock on to reference signals from GPS satellites (e.g., 20, 22),
15   and then each receiver 16, 18 performs a carrier phase measurement on a satellite reference signal transmission that it is tracking. This measurement consists of a fractional phase part ϕ and an integer count N of phase cycles from an initial epoch t_0 to epoch t.

In the following paragraph, a single difference technique is described,
20   although the embodiments described herein can also be applied to a double difference technique. Referring to Figure 1, antenna 10 of receiver 16 is a distance d away from antenna 12 of receiver 18. Both receivers 16 and 18 receive signals from a satellite, for example 20, at an elevation θ, which is essentially identical for both receivers 16 and 18 because of the distance of satellite 20. However, the distance from each
25   receiver 16 and 18 from satellite 20 is different by a measurable amount. Letting ϕ_1^q denote a phase measurement made by receiver 16 and ϕ_2^q denote a phase

measurement made by receiver 18 for a qth satellite (e.g., $q=1$ for satellite 20, $q=2$ for satellite 22), a scaled difference $\Delta\phi_1^q$ is given by:

$$\Delta\phi^q = (\phi_1^q - \phi_2^q) = \lambda(N_1^q - N_2^q) + c(\Delta t_1^q - \Delta t_1^q) + \vec{d} \bullet \vec{h}$$

where $\Delta\phi^q$ is the single difference for the qth satellite;

$\vec{h}$ is a unit vector in the direction of satellite q,

$\vec{d}$ is a vector distance between the two antennas 10 and 12,

N_p^q is an integer phase count for the pth receiver (e.g., $p=1$ or 2 for receiver 16 or 18, respectively) and for the qth satellite;

Δt_p^q is an error associated with the pth receiver for the qth satellite;

c is the speed of light; and

λ is a wavelength of the radio signal received from the qth satellite.

To solve for $\vec{d}$, it is assumed that the clock error and the integer ambiguity between both receivers to the satellites are known. The measurements are made to each of n satellites in the GPS system, and integer phase counts and clock errors are known or determined. The following are written, where LOS_x^q, LOS_y^q, and LOS_z^q are the x, y, and z vector components in the east, north, and up coordinate system of a line of sight to the qth satellite:

$$\mathbf{H} = \begin{bmatrix} LOS_x^1 & LOS_y^1 & LOS_z^1 \\ LOS_x^2 & LOS_y^2 & LOS_z^2 \\ \vdots & \vdots & \vdots \\ LOS_x^n & LOS_y^n & LOS_z^n \end{bmatrix}$$

$$\vec{y} = \begin{bmatrix} \Delta\phi^1 - \lambda(N_1^1 - N_2^1) - c(dt_1 - dt_2) \\ \Delta\phi^2 - \lambda(N_1^2 - N_2^2) - c(dt_1 - dt_2) \\ \vdots \\ \Delta\phi^n - \lambda(N_1^n - N_2^n) - c(dt_1 - dt_2) \end{bmatrix}$$

$$\vec{d} = \begin{bmatrix} d_x \\ d_y \\ d_z \end{bmatrix}$$

Vector $\vec{d}$ is a vector representing a baseline in an x, y, and z coordinate system, representing east, north, and up, respectively. Using the above equations, the following is also written:

$$\vec{y} = H\vec{d}$$

A solution to the above equation is written:

$\vec{d} = (H^T H)^{-1} H^T \vec{y}$, subject to the additional condition that:

$\| \vec{d} \| = $ a distance between antennas 10 and 12.

In another aspect of the present invention, double differencing, as known to those skilled in the art, is used to eliminate clock errors of receivers 16 and 18.

Locomotive 14 rides on a track having limited pitch. Maximum pitches range up to about 2 to 3 percent. Therefore, it is much easier to apply the constraint on $\| \vec{d} \|$ and to solve for integer ambiguities of N_p^q than in more general cases. Once $\vec{d}$ is determined, an attitude of locomotive 14 is determined at every epoch. By computing differences in the attitude, the attitude rate is computed. Clock errors and integer ambiguities are readily computed, so that a continuous

measurement of heading and heading rate is output from GPS receivers 16 and 18. In

particular, heading is given by $\tan^{-1}\dfrac{d_x}{d_y}$, and pitch is given by $\dfrac{\tan^{-1}d_z}{\sqrt{d_x^2 + d_y^2}}$. Thus, a

continuously updated attitude and attitude rate are available. It is only necessary that receivers 16 and 18 maintain phase lock with received signals from the GPS satellites 20, 22... up to an nth satellite. If phase lock is not maintained cycle slip will occur at which time integer ambiguities will have to be recalculated. Microprocessor 24 coupled to receivers 16 and 18 is used, in one embodiment, to compute at least one of an accurate heading and heading rate. As used herein, microprocessor 24 refers to controllers and processors, including microcontrollers, programmable logic controllers, input/output controllers, reduced instruction set circuits, application specific integrated circuits, logic circuits, and any other circuit, processor or microcomputer capable of processing the embodiments described herein. For example, results are displayed on display 26 or recorded on an internal or external device 28 such as a hard disk or magnetic tape or sent to a navigational computer . In one embodiment, device 28 is a transmitter configured to relay computed location and/or motion information to another location.

A present absolute position of locomotive 14 measured in latitude and longitude is provided by GPS receivers 16 and 18. To resolve an initial integer ambiguity, determine clock offsets, or both, a database 30 is consulted to provide initial heading and grade of a track as a function of the latitude and longitude information. Given LOS values, three unknown parameters d_x, d_y, and d_z are directly

obtained by computation subject to the constraint that a magnitude of $\vec{d}$ is equal to a

distance between antennas 10 and 12.

In yet another embodiment and referring to Figure 2, track database 30 contains measured or otherwise known track curvatures, indexed by location. A single GPS receiver and antenna, for example GPS receiver 16 and antenna 12, provides a position signal 54 (in addition to any other signals provided for other purposes). Using a location inferred from position signal 54, track database 30 is consulted to determine track curvature C at that location.

Another aspect of the invention is detection of curves and reduction of track wear. Referring to Figures 3 and 4, when wheels 32 of locomotive 14 move over curve 34 on a track 36, resulting friction causes track 36 to wear down. A track is worn down, for example, when a crown (not shown) has worn off. By detecting

5   curve 34 and dispensing a lubricant 38 to rails of track 36 while locomotive 14 negotiates curve 34, wear of track 36 rails is reduced. The lubricant 38 may be dispensed from a lubricating system or any system for lubricating the rails of track 36, including lubricant dispenser 44.

Referring to Figure 5, curves 34 are detected in one embodiment by

10   utilizing a gyroscope 40 to detect an angular rotation rate ω and a tachometer 42 to detect a train velocity v. Curvature C is then written $C=\omega/v$. One or more lubricant dispensers 44 are configured to dispense lubricant 38 to track 36 rails. Specifically, lubricant dispensers 44 are operated by a microprocessor 24, for example, the microprocessor 24 of Figure 2. Microprocessor 24 is responsive to an angular change

15   signal 46 related to ω and a tachometer signal 48 related to velocity v to operate lubricant dispenser 44 to dispense lubricant 38 to track 36 rails when a predetermined magnitude of curvature C is exceeded.

In another embodiment and referring to Figure 6, an angular change signal (not shown) is determined by microprocessor 24 utilizing signals supplied from

20   a pair of GPS receivers 16 and 18 (such as those also shown in Figure 2) from signals received at antennas 10 and 12, respectively. This angular change signal is easily obtained because one attribute of attitude is a heading h, and $\Delta h/\Delta t=\omega$. Tachometer 42 supplies a tachometer signal 48 in this embodiment, and microprocessor 24 computes $C=\omega/v$.

25   In yet another embodiment and referring to Figure 7, a lateral accelerometer 50 produces or generates a lateral acceleration signal a. Microprocessor 24 is responsive to accelerometer 50, signal 52 and tachometer signal 48 to control lubricant dispensers 44. Lubricant 38 is dispensed when a predetermined magnitude of curvature C, as determined by a ratio a/v^2, is exceeded.

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Lubricant 38 is applied to reduce friction between wheels 32 and track 36 rails when a magnitude of curvature C is exceeded by an amount to make track wear a concern. Accordingly, in one embodiment, lubricant dispensers 44 are configured to dispense lubricant 38 to wheels 32 rather than directly on track 36 rails.

5   In embodiments in which measurement accuracy is unacceptably compromised by selective availability (SA), differential GPS (DGPS) is used. (SA results from a time-varying drift that either is, or that can be added deliberately to GPS satellite signals to limit absolute measurement accuracy for commercial and non-military applications.)

10   Using one of receivers 16 or 18 in conjunction with microprocessor 24, another aspect of the present invention provides accurate measurements of distance traveled by the locomotive 14. However, it will be recognized that this aspect of the invention is also applicable to other land-based vehicles, as well. In one embodiment, a distance traveled is accurately determined even in the presence of SA with or
15 without external DGPS connections. Samples of latitude and longitude from one of the receivers, for example, receiver 16, is sampled frequently enough so that errors in these samples are highly correlated. For example, samples are taken about every second. A distance between the samples is computed as a function of differential latitude and longitude. The difference Δd is written as follows:

20    $$\Delta d = R[\Delta lat^2 + \cos^2 (lat) \Delta long^2]^{1/2}$$

where Δlat is a difference between latitudes of consecutive measurements;

$\Delta long$ is a difference between longitudes of consecutive measurements; and

25   R is the radius of the earth (about 3,440 nmi).

A total distance traveled is a summation of Δd over successive measurements. This distance measurement is accurate even though absolute latitude

and longitude measurements are subject to large errors, because these errors are highly correlated between consecutive measurements and cancel out when differences are calculated. Even errors resulting from selective availability are readily cancelled by this method.

5   From the preceding description of various embodiments of the present invention, it is evident that navigational parameters of a locomotive are efficiently and inexpensively measured utilizing two GPS receivers, and track wear is reduced through efficient use of lubricant.

           Even though a GPS satellite system is described, any satellite system

10   or network may be utilized, for example, GPS, DGPS, and Glonass.

           Although the invention has been described and illustrated in detail, it is to be clearly understood that the same is intended by way of illustration and example only and is not to be taken by way of limitation. Accordingly the spirit and scope of the invention are to be limited only by the terms of the appended claims and their

15   equivalents.

WHAT IS CLAIMED IS:

1.   A method for determining at least one of motion and location parameters of a locomotive, said method comprising the steps of:

determining a set of phase differences between satellite reference signals received by satellite receivers; and

determining at least one of an accurate heading, heading rate, attitude, and attitude rate of the locomotive using the set of phase differences between the satellite reference signals.

2.   A method according to Claim 1 further comprising the step of determining $\vec{d}$.

3.   A method according to Claim 2 further comprising the step of determining $\vec{d}$ as $\vec{d} = (H^T H)^{-1} H^T \vec{y}$, where:

$$H = \begin{bmatrix} LOS_x^1 & LOS_y^1 & LOS_z^1 \\ LOS_x^2 & LOS_y^2 & LOS_z^2 \\ \vdots & \vdots & \vdots \\ LOS_x^n & LOS_y^n & LOS_z^n \end{bmatrix};$$

$$\vec{y} = \begin{bmatrix} \Delta\phi^1 - \lambda(N_1^1 - N_2^1) - c(dt_1 - dt_2) \\ \Delta\phi^2 - \lambda(N_1^2 - N_2^2) - c(dt_1 - dt_2) \\ \vdots \\ \Delta\phi^n - \lambda(N_1^n - N_2^n) - c(dt_1 - dt_2) \end{bmatrix}; \text{ and}$$

$$\vec{d} = \begin{bmatrix} d_x \\ d_y \\ d_z \end{bmatrix}.$$

4.   A method according to Claim 3 wherein said step of determining at least one of an accurate heading, heading rate, attitude, and attitude rate of the locomotive further comprises the step of determining an attitude and an attitude rate of a locomotive using $\vec{d}$, the heading using $\tan^{-1}\dfrac{d_x}{d_y}$, and heading rate

5   using $\dfrac{\tan^{-1} d_z}{\sqrt{d_x^2 + d_y^2}}$.

5.   A method according to Claim 1 further comprising the step of determining a track curvature, C.

6.   A method according to Claim 5 wherein determining a track curvature comprises the step of detecting an angular rotation rate ω and a velocity v of

10   the locomotive, wherein $C = \omega / v$.

7.   A method according to Claim 6 wherein detecting an angular rotation rate ω and a velocity v of the locomotive comprises the step of detecting an angular rotation rate ω using a gyroscope and a velocity v of the locomotive using a tachometer.

15   8.   A method according to Claim 6 wherein detecting an angular rotation rate ω and a velocity v of the locomotive comprises the step of detecting an angular rotation rate ω using received satellite signals and velocity v of the locomotive using a tachometer.

9.   A method according to Claim 5 wherein determining a track

20   curvature comprises the step of determining a lateral acceleration a and a velocity v of the locomotive, wherein $C = a / v^2$.

10.   A method according to Claim 5 further comprising the step of controlling dispensing of a track lubricant in accordance with the determined curvature value C.

11.　A method according to Claim 10 wherein said step of controlling dispensing of a track lubricant further comprises the step of dispensing the lubricant when C exceeds a predetermined magnitude.

12.　A method according to Claim 1 further comprising the steps of:

5　　　　　　　　　　determining a position of the locomotive; and

accessing a database of track heading and grade to determine a present track heading and grade at the determined position of the locomotive.

13.　A method according to Claim 1 further comprising the steps of:

sampling latitude and longitude from the satellite receivers; and

10　　　　　　　　　　determining a distance traveled by the locomotive.

14.　A method according to Claim 13 wherein said step of sampling latitude and longitude from the satellite receivers further comprises the steps of:

sampling where the distance between the samples is determined as

$$\Delta d = R[\Delta lat^2 + \cos^2(lat)\Delta long^2]^{1/2}$$

15　　　　　　　　　　where Δlat is a difference between latitudes of consecutive measurements;

$\Delta long$ is a difference between longitudes of consecutive measurements; and

R is the radius of the earth (about 3,440 nmi); and

20　　　　　　　　　　said step of determining a distance traveled by the locomotive further comprises the step of summing Δd over successive measurements.

15.　An apparatus for determining at least one of motion and location parameters of a locomotive to detect curves and reduce track wear, said apparatus comprising:

12

at least two phase-locking satellite receivers configured to reference signals received from a set of satellites; and

a processor configured to determine a set of phase differences between the reference signals received by said satellite receivers and at least one of an accurate heading, heading rate, attitude, and attitude rate of the locomotive using the set of phase differences between the reference signals.

16.   An apparatus according to Claim 15 wherein said processor further configured to determine $\vec{d}$.

17.   An apparatus according to Claim 16 wherein said processor further configured to determine $\vec{d}$ as $\vec{d} = (H^T H)^{-1} H^T \vec{y}$, where:

$$H = \begin{bmatrix} LOS_x^1 & LOS_y^1 & LOS_z^1 \\ LOS_x^2 & LOS_y^2 & LOS_z^2 \\ \vdots & \vdots & \vdots \\ LOS_x^n & LOS_y^n & LOS_z^n \end{bmatrix};$$

$$\vec{y} = \begin{bmatrix} \Delta\phi^1 - \lambda(N_1^1 - N_2^1) - c(dt_1 - dt_2) \\ \Delta\phi^2 - \lambda(N_1^2 - N_2^2) - c(dt_1 - dt_2) \\ \vdots \\ \Delta\phi^n - \lambda(N_1^n - N_2^n) - c(dt_1 - dt_2) \end{bmatrix}; \text{ and}$$

$$\vec{d} = \begin{bmatrix} d_x \\ d_y \\ d_z \end{bmatrix}.$$

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18.   An apparatus according to Claim 17 wherein said processor further configured to determine an attitude and an attitude rate of the locomotive using $\vec{d}$, the heading using $\tan^{-1}\dfrac{d_x}{d_y}$, and the heading rate using $\dfrac{\tan^{-1}d_z}{\sqrt{d_x^2+d_y^2}}$.

19.   An apparatus according to Claim 15 wherein said processor further configured to determine a track curvature, C.

20.   An apparatus according to Claim 19 wherein to determine a track curvature, said processor configured to detect an angular rotation rate ω and velocity v of the locomotive.

21.   An apparatus according to Claim 20 wherein to detect an angular rotation rate ω and velocity v of the locomotive, said processor configured detect an angular rotation rate ω using received satellite signals and velocity v of the locomotive using a tachometer.

22.   An apparatus according to Claim 20 wherein to detect an angular rotation rate ω and velocity v of the locomotive, said processor configured detect an angular rotation rate ω using a gyroscope and velocity v of the locomotive using a tachometer.

23.   An apparatus according to Claim 19 wherein to determine a track curvature, said processor further configured to:

       determine a lateral acceleration a and a velocity v of the locomotive; and

       determine track curvature C as: $C = a / v^2$.

24.   An apparatus according to Claim 19 further comprising a device for dispensing a lubricant to a track.

25.   An apparatus according to Claim 24 wherein said processor further configured to control said device dispensing the lubricant in accordance with the determined curvature value C.

26.   An apparatus according to Claim 25 wherein said processor further configured to dispense the lubricant when C exceeds a predetermined magnitude.

27.   An apparatus according to Claim 24 wherein said processor further configured to:

determine a position of the locomotive;

access a database of track heading and grade to determine a present track heading and grade at the determined position of the locomotive; and

control said device dispensing lubricant in accordance with a curvature value C contained within the track database.

28.   An apparatus according to Claim 15 wherein said processor further configured to:

sample latitude and longitude from the GPS receivers; and

determine a distance traveled by the locomotive.

29.   An apparatus according to Claim 28 wherein said processor configured to determine a distance between samples as:

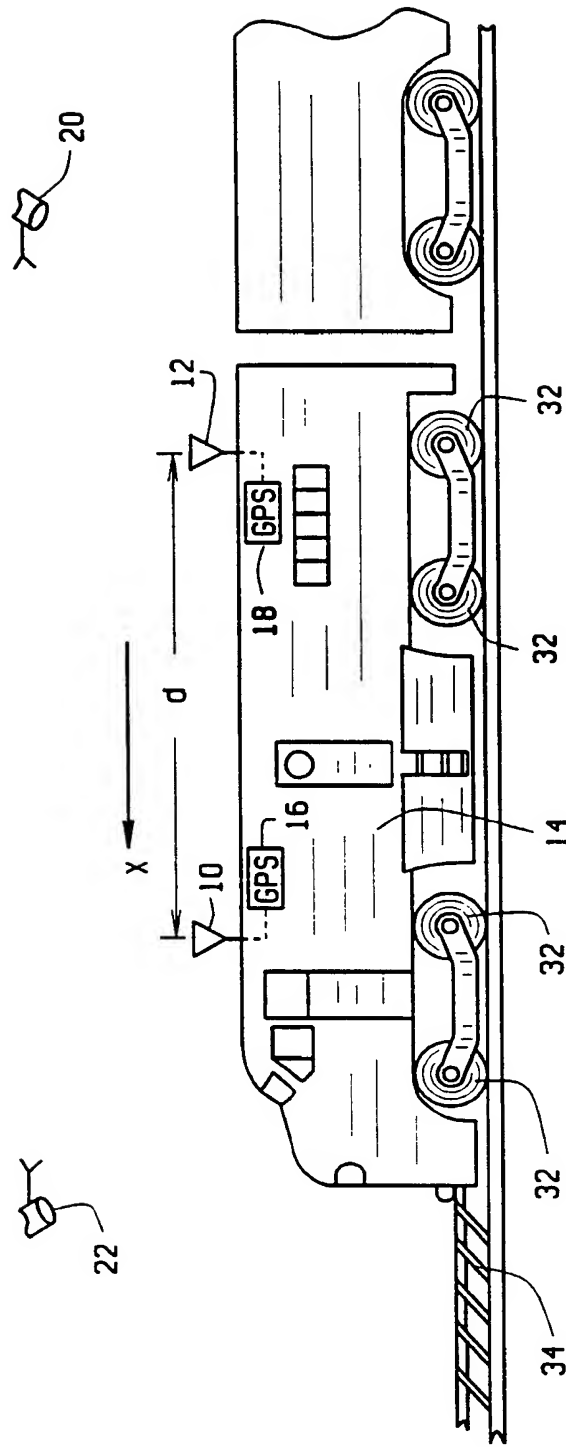$$\Delta d = R[\Delta lat^2 + \cos^2(lat)\Delta long^2]^{1/2}.$$

FIG. 1

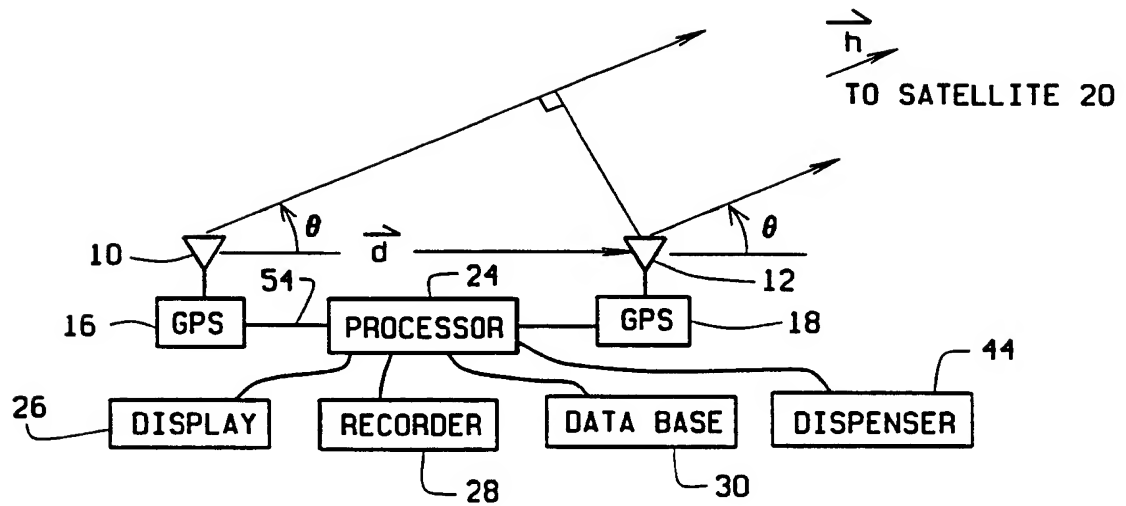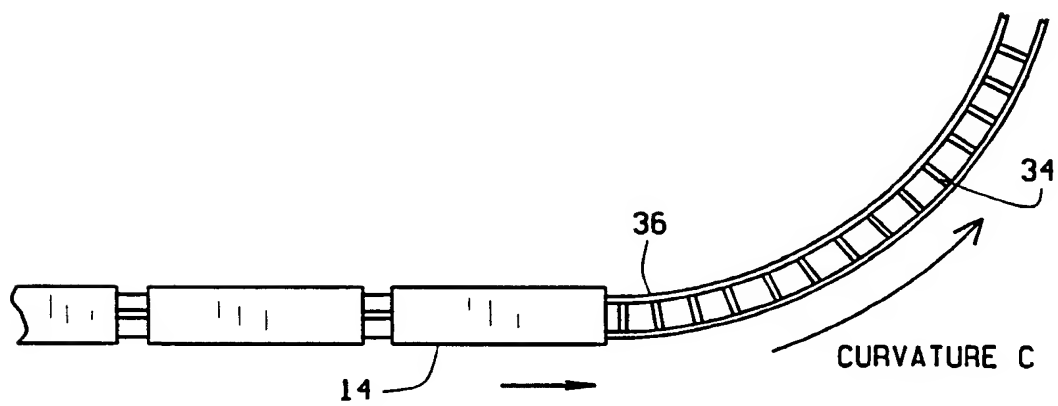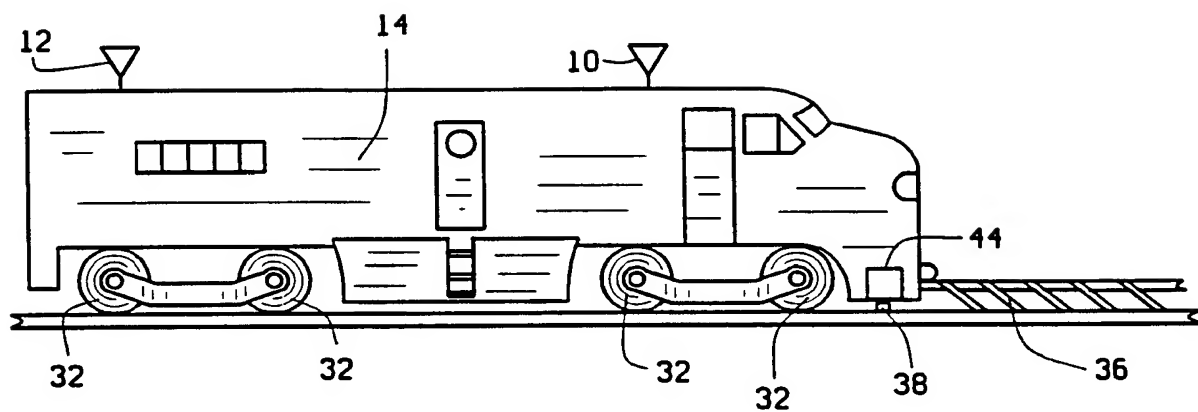$\vec{h}$
TO SATELLITE 20

10   θ $\vec{d}$ θ 12

54

16 — GPS   PROCESSOR — 24   GPS — 18

26 — DISPLAY   RECORDER   DATA BASE   DISPENSER — 44

28   30

FIG.2

34

36

14

CURVATURE C

FIG.3

FIG.4
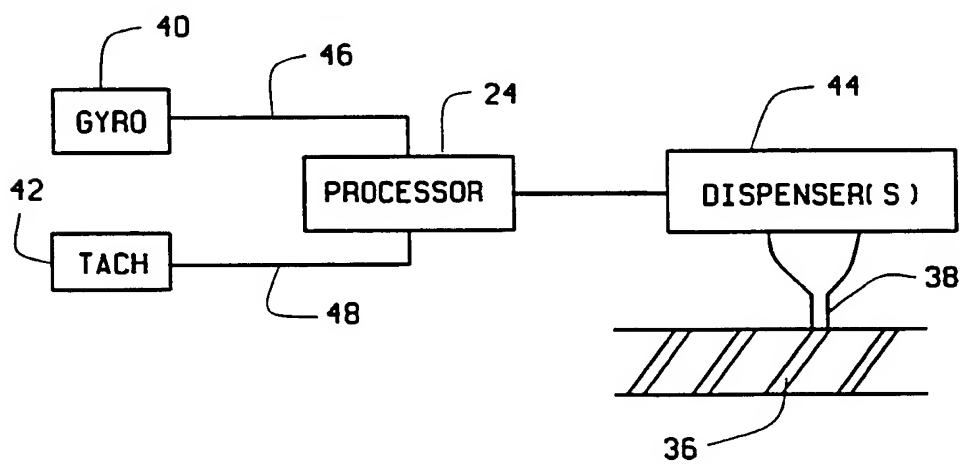
FIG.5
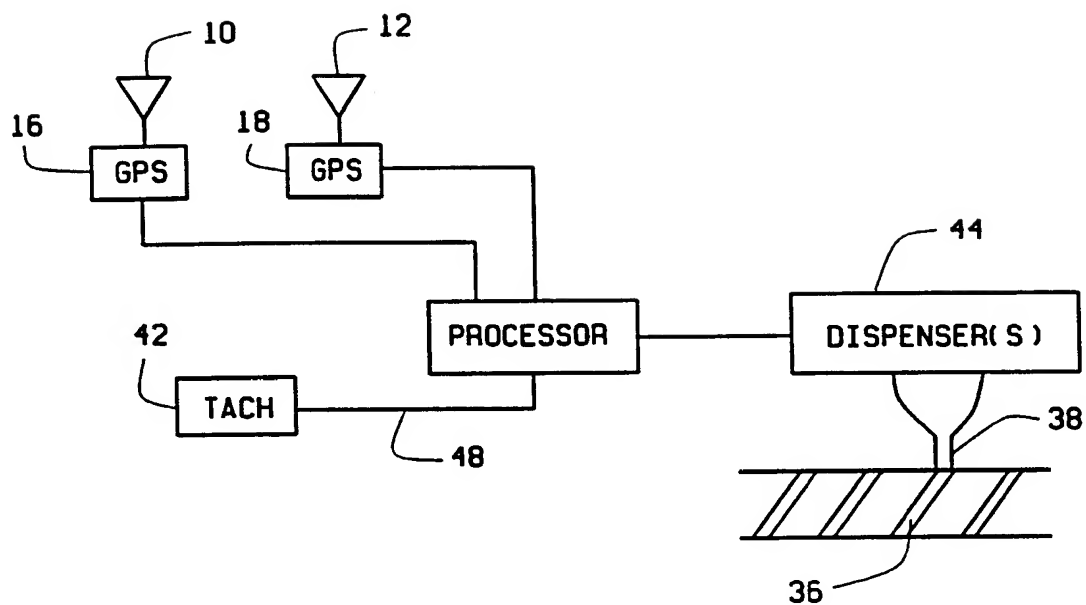
FIG.6

FIG.7

INTERNATIONAL SEARCH REPORT

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7   G01S5/02   B61K3/02

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7   G01S   B61K

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, WPI Data, PAJ, INSPEC

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category°	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	WO 98 29757 A (HONEYWELL INC) 9 July 1998 (1998-07-09)	1-3,5, 12,13, 15-17
A	page 2, line 29 -page 3, line 13 page 10 -page 11/1 ---	4,6-11, 14,18-24
Y	EP 0 893 323 A (WESTINGHOUSE AIR BRAKE CO) 27 January 1999 (1999-01-27) column 11, line 8 - line 50 ---	1-3,5
Y	DE 196 32 958 C (REBS ZENTRALSCHMIERTECH GMBH) 29 January 1998 (1998-01-29)	12,15-17
A	column 1, line 58 -column 3, line 57 --- -/--	4,6-11, 14,18-24

[X] Further documents are listed in the continuation of box C.   [X] Patent family members are listed in annex.

° Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

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"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

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"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
29 November 2000	07/12/2000

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL – 2280 HV Rijswijk Tel. (+31–70) 340–2040, Tx. 31 651 epo nl, Fax: (+31–70) 340–3016	Ó Donnabháin, C

1

Form PCT/ISA/210 (second sheet) (July 1992)

INTERNATIONAL SEARCH REPORT

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
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